(54) Title: APPARATUS AND METHOD FOR SENSING INTRAVASCULAR PRESSURE
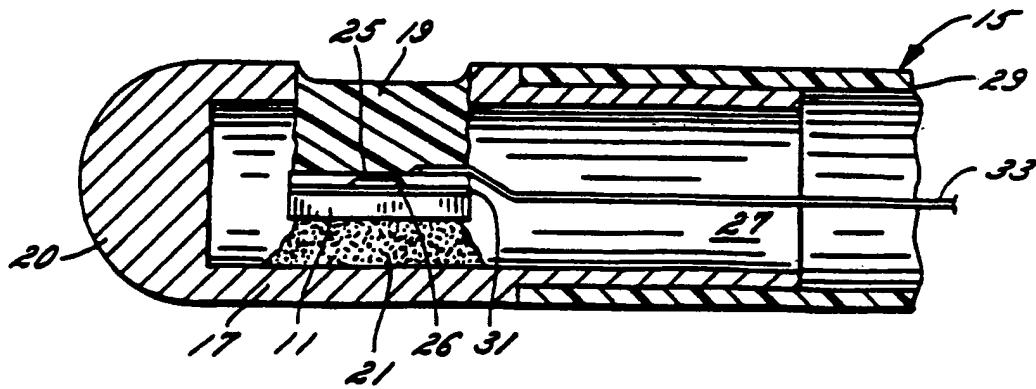
(57) Abstract

A pressure sensor assembly (11) is provided for placement within the tip of a conventional catheter (15) or the like for insertion into a small cavity such as a human coronary artery. The pressure sensor assembly (11) is comprised of device and backing dies (67 and 75) of crystalline material bonded together without the use of a bonding material, thereby providing direct contact between the two crystalline dies. A diaphragm (25) is etched into one of the dies before it is bonded to the other die. A cavity (26) formed by the diaphragm when the two dies are bonded is vented to a reference atmosphere by a channel or groove (31) in the backing die. During the fabrication of the sensor assembly, small holes (71) are etched completely through the wafer (75) used to form the device dies in order to provide targets for alignment during the fabrication of the sensor assembly. Finally, the fabrication of circuitry on the wafer forming the device dies includes providing complementary temperature coefficients of the nominal piezoresistance and of the piezoresistive coefficient.

APPARATUS AND METHOD FOR SENSING INTRAVASCULAR PRESSURE

TECHNICAL FIELD

The invention generally relates to the measuring of pressure utilizing a catheter equipped with a pressure sensing apparatus and, more particularly, to the recording of physiological pressure for vascular application, such as peripheral blood vessels, chambers of the heart and coronary arteries, and non-vascular applications, such as intrauterine or intracranial pressures and the like.

BACKGROUND OF THE INVENTION

Very accurate, distortion-free recordings of blood pressure waveforms are often required in many critical care or interventional clinical situations. This is typically done through the use of a saline-filled catheter, the distal end of which is located at the measurement site. Outside the body, the proximal end of the catheter is connected to an external pressure transducer. The pressure in the vessel is transmitted via the fluid column, detected by the transducer and displayed by suitable electronic means. For example, the precise measurement of haemodynamic pressures can be an important adjunct to surgical procedures such as angioplasty. It is known that the differential blood pressure across a lesion, known as the pressure gradient, can be correlated to successful treatment. Typically, the aim is to reduce the pressure gradient to a minimally acceptable value, implying that the lesion has been dilated to an acceptable level, and minimizing the need to repeat the procedure. The current technique utilizes the guidewire lumen of a balloon catheter to communicate the intravascular pressure to a pressure transducer located outside the body.

2

Several problems are known to exist with the
external transducer technique. For example, the
fluid column may not give a true transmission of the
waveform due to the damping or ringing within the
tube. The possibility of introducing air into the
vasculature exists which, of course, is potentially
dangerous. The catheter itself can obstruct the flow
of blood due to its size relative to small vessel
lumen. Many balloon catheters cannot be used to make
pressure measurements since their lumens are too
small to yield satisfactory results.

As a group, these type of pressure sensors are
typically referred to as external fluid-column
transducers and are presently in common use. ·In
addition to the foregoing limitations, this type of
transducer has significant additional limitations
which makes it less than completely satisfactory for
use in patient monitoring, particularly critical care
situations. For example, the set-up of the catheter
is difficult and time consuming. Because of the
fluid column, there is a potential for patient
contamination. Also distortion in the pressure
reading may result from motion artifacts, kinking in
the catheter line or air bubbles present in the
system. All of the foregoing limitations are
directly or indirectly related to the fluid column
which propagates the pressure sensed at the tip of
the catheter to the external pressure transducer.

A second type of pressure sensing device, which
may be fitted to the distal end of a catheter, is a
semiconductor device which senses stress of a
semiconductor crystal structure in response to the
pressure of the ambient environment. The semicon-
ductor material includes piezoresistive elements
which respond to the stress by changing electrical

3

resistance to current flow. This resulting electrical signal can be detected by an external measuring device via wires threaded through the catheter. There is, therefore, no need for a fluid column as a transmission medium.

These catheter tip pressure sensing devices have many advantages over the fluid-column devices. For example, the set-up is simpler and less time consuming. The risk of contamination is substantially less, and the risk of introducing an air bolus into the patient is eliminated. Finally, since the pressure waveform is transduced at the site of measurement, its electrical representation is distortion free.

Unfortunately, the semiconductor pressure sensors which fit on the tip of a catheter are relatively fragile and expensive. Also, they are not available in small sizes for use in measuring pressure in small cavities such as coronary arteries. In this connection, they are usually of such large sizes that an extra lumen for a guide wire cannot be provided. Moreover, the catheter tip pressure sensors may require special interface circuits at the proximal end of the catheter in order to match the transducer output with standard monitoring devices.

SUMMARY OF THE INVENTION

It is a primary object of the invention to provide a semiconductor-based pressure transducer which is small enough to be encapsulated within a catheter for insertion into very small body cavities such as the coronary arteries. In this connection, it is an object of the invention to provide a semiconductor sensor which can be fitted to the distal

4

end of a catheter while maintaining room for an extra
lumen for purposes such as the insertion of a
guidewire, sampling of body fluids and the like.

It is a related object of the present invention
to produce a semiconductor pressure transducer device
meeting the foregoing size requirements which has a
structural integrity sufficient to withstand the
stresses produced by movement of the catheter when in
its in vivo position.

Another object of the invention is to provide a
device having the foregoing qualities which has a
substantially constant sensitivity to pressure
throughout the biological temperature range. In this
connection, it is a related object of the present
invention that the transducer device has a
substantially linear response to pressure throughout
the biological temperature range.

Another object of the present invention is to
provide a pressure sensitive transducer device which
is electrically compatible with standard medical
display devices or recording equipment. More
particularly, it is an object of the present
invention to provide a transducer device which does
not require additional amplification or processing
equipment in order to interface with the standard
medical monitoring devices.

It is another object of the invention to provide
a pressure sensitive transducer device which is of
sufficiently low cost that the device is essentially
disposable.

It is still another object of the present
invention to provide a transducer device which
exhibits substantially distortion-free frequency
response through the physiological range.

Other objects and advantages of the invention
will be apparent from the following summary and
detailed description and the accompanying drawings.

The invention utilizes a unique process for
forming a miniaturized semiconductor pressure trans-
ducer. In connection with the process for making the
miniature transducer of the invention, several design
criteria have been identified which complement the
unique process in order to minimize the sensor die
size. Other novel design features of the sensor
maintain a desired performance level at these reduced
dimensions. As currently fabricated, the length,
width and thickness of the die is .040 inches by
.020 inches by .011 inches, respectively. However,
the design and fabrication procedures of the
invention can also be used to produce smaller
devices. In accordance with the invention, a number
of silicon wafer fabrication techniques are combined
in a particular, unique sequence in order to achieve
the small die size for the pressure sensing
transducer. In addition, there are specific novel
design features of the sensor which allow it to
achieve a desired performance level within catheters.

As is known in the art, semiconductor pressure
sensors are typically fabricated by etching a thin
diaphragm from a portion of a silicon die so that the
diaphragm flexes slightly upon application of a
stress. From two to four piezoresistive elements are
then implanted into the surface of the diaphragm,
oriented to particular crystal axes and configured as
a half or full bridge circuit. When stress is
applied, the resistors change electrical
characteristics (the piezoresistive effect) to a
sufficient degree that the bridge imbalance can be
detected in response to an applied voltage or

6

current. With proper design, the piezoresistive
effect can be made linear over a given range of
stresses. The piezoresistive effect is most
pronounced in silicon of a <100> crystal orientation,
hence this is the material of choice for the wafer
from which the die is formed.

The critical design consideration which deter-
mines how small the sensor die can be made is the
minimum dimension diaphragm which can be realized for
a given wafer thickness while maintaining a struc-
turally adequate rim of thick silicon around the
diaphragm. In order to etch a diaphragm into a
silicon wafer of <100> crystal orientation, an aniso-
tropic etchant must be used which produces a thinning
of the wafer along <111> crystal planes at an angle
of 54.7° to the surface. The ratio of the thickness
of the diaphragm to that of its length should be 1:60
or more in order to achieve sufficient flexibility.
Since there must also be a suitable border of thick
silicon remaining for structural integrity of the
die, the thickness of the wafer becomes the limiting
factor in determining die size.

Sufficient thickness of the wafer is required to
ensure that the wafer does not shatter during
processing. In conventional wafer fabrication
technology, wafers with a thickness of .012 to
.015 inches or more are used to minimize breakage.
For pressure sensors, this limits the minimum die
size possible due to the etch angle constraint
explained above such that only large die can be
realized which are not suited for small catheters.
As an example, for a .015-inch thick wafer, in order
to produce a die with a diaphragm of length
.010 inches, a die of width .037 inches is required,
allowing a thick silicon edge of .003 inches. In the

7

present invention, the same diaphragm length of
.010 inches can be realized in a die of .020 inch
width with the same .003 inch thick silicon edge.

In conventional processing, the circuitry is
fabricated first onto the wafer and the last step of
the process involves etching the diaphragm. In the
conventional sequence, a thick wafer must be used in
order to accommodate all of the high temperature and
cleaning steps required to fabricate the circuitry.

In contrast to the conventional approach, the
fabrication process of the invention provides for the
etching of a diaphragm into a thin wafer prior to the
fabrication of the circuitry onto the wafer. After
the diaphragm is etched, the thin wafer is bonded to
a thicker wafer in order to provide the mechanical
support necessary for the other processing steps such
as circuit fabrication. The method of bonding the
two wafers is a critical step for proper functioning
of the pressure sensing device of the invention. If
the bonding of the wafer is done using a dissimilar
material (e.g., silicon diioxide or glass), different
temperature coefficients of expansion of the
materials will cause poor operation of the device at
different temperatures due to differential
stresses. In the present invention, a thin silicon
wafer is bonded directly to a thicker silicon wafer
without a third material as a bonding agent. This is
done by thorough cleaning of the surfaces under class
10 or better clean room conditions followed by a heat
treatment. In accordance with this method, no
temperature-induced stresses occur since dissimilar
materials are not introduced at an interface between
the two wafers. Subsequent to the bonding of the two
wafers, the other process steps required to fabricate
the electronic circuitry are performed.

8

    In forming the diaphragm on the thin wafer, a
critical parameter which must be controlled is the
thickness of the diaphragm. If the thickness varies
between dice, a variation in the sensitivity of each
die results, thereby decreasing the ability to
produce a low-cost standard device. Several methods
of thickness control are well known, and for the
precise control of diaphragm thickness, the method of
electrochemical etch stopping is believed by appli-
cants to be the best technique, and is accordingly a
preferred method for this invention. To applicants'
knowledge, this method has not been applied to
produce diaphragms as thin (e.g., 3-4 microns) as are
required in the present invention. As set forth
hereinafter, applicants have modified the conven-
tional method of electrochemical etch stopping to
include a particular process of wafer preparation and
a special purpose fixture to ensure that the proper
electrical bias parameters are present on the wafer
surface during the etching procedure. Failure to
provide these conditions results in a premature etch
stop in a diaphragm which is too thick or non-
uniformly etched.

    The net pressure detected by a sensor is the
difference between the pressures on the two sides of
the diaphragm. In the present invention, one side of
the diaphragm is vented to the atmosphere, and it is
typically called the reference side. In prior art
devices, since the diaphragm is etched as the last
step in fabrication, the entire back surface of the
diaphragm is open for venting to the atmosphere.
When the die is subsequently mounted to a backing
plate (usually of amorphous glass or metal), a hole
is drilled through the backing plate as a vent. In
the present invention, however, the wafer which has

9

been etched to form a diaphragm and the backing or support wafer are bonded in an early step of the fabrication. A reference channel which vents the reference side of the diaphragm to atmosphere is provided in a novel manner by chemically etching a groove into the surface of the backing wafer along the length axes of the wafer. When the thin wafer containing the diaphragm is bonded to the support or backing wafer, the groove forms a channel through the die which communicates the reference side of the diaphragm to the atmosphere surrounding the die. During encapsulation of the die in a catheter, the vent provides a means for communicating atmospheric pressure from the outside of the patient's body through a connector affixed to the proximal end of . the catheter to the reference side of the diaphragm.

Normal process tolerances during fabrication of the piezoresistors on the diaphragm result in different nominal values for the resistors. Upon excitation of the bridge network formed by the piezo-resistors, the slight difference in nominal values produces an unstressed offset which must be reduced to an acceptable value. In accordance with the invention, the offset reduction is accomplished on-board the die by including in one arm of the bridge network a resistor trim ladder network. This resistor trim ladder network is a thin film network which is deposited by conventional metal sputtering. Each element of the resistor trim ladder is accessible electronically through a contact pad so that any combination of resistor values up to a defined maximum may be trimmed into the bridge circuit in order to zero the unstressed offset value. Alternatively, the resistor trim ladder may be adjusted by means of a laser beam.

Each piezoresistor has a temperature coefficient
of resistance (TCR) which defines the amount of
change in resistance of piezoresistors with respect
to temperature at a constant pressure. As discussed
more fully hereinafter, the four piezoresistors are
fabricated so as to have nearly the same TCR
values. Therefore, if the piezoresistors are closely
matched, they will each vary in response to tempera-
ture changes by approximately the same amount. In
the balanced bridge network, the changes in resis-
tance in response to temperature will effectively
cancel, thereby maintaining a zero unstressed offset
value. However, if the thin film network has a
different TCR value, errors will be introduced in
response to temperature fluctuations.

In accordance with another aspect of the present
invention, the TCR value of the piezoresistors is
matched to the TCR value of the alloy chosen for the
thin film trim network. By matching these TCR
values, the trim network may be used to successfully
balance the bridge network during calibration and
will thereafter maintain the balance in response to
temperature variations. In the preferred embodiment,
the temperature variation range is between 15 and 40°
Centigrade, since this is the temperature range
between the normal ambient environment surrounding a
patient and the patient's body temperature.

For a given diaphragm geometry and resistor
placement, the magnitude of the voltage output of the
bridge network is a function of temperature and
pressure, and is dependent on the TCR value of the
piezoresistors, the temperature coefficient of the
piezoresistive coefficient of the piezoresistors
(TCPI) and external span resistors (if any). The
TCPI means that the sensitivity of the bridge to

pressure changes is a function of temperature. The
TCR of the piezoresistors will cause resistance of
the bridge network to increase with temperature. By
placing the sensor in series with external span
resistors that have a TCR of zero, the voltage drop
across the bridge network changes in response to
changes in ambient temperature. Although the
sensitivity of the network may have been altered by
the TCPI in response to a change in temperature, the
change in the voltage drop across the bridge network
caused by the TCR serves to maintain the same output
magnitudes for given pressure differentials across
the diaphragm. By careful application of conven-
tional design techniques, the TCR values of the
piezoresistors can be made to offset their TCPI
values for certain values of resistors located off-
chip. In other words, when a temperature change
occurs, the TCR of the piezoresistors will increase/
decrease the magnitude of the signal from the bridge
network by an amount equal to the decrease/increase
caused by the TCPI.

In the present invention, the doping of the
piezoresistors is chosen to maximize piezoresistive
coefficients and to minimize the piezoresistive
sensitivity to small changes in the doping level,
thereby assuring uniformity among different trans-
ducers.

Since the transducer of the invention is
intended to be incorporated into the distal end of a
catheter, power dissipation on the chip is an
important consideration. Not only should the
temperature of the catheter tip remain within
physiological limits, but performance of the device
is enhanced by minimizing self-heating of the chip
because of the temperature considerations discussed

12

above. An off-chip resistor network located in the
electrical connector joining the proximal end of the
catheter to the standard measuring equipment
dissipates much of the power at an external location,
thereby minimizing self-heating.

Additionally, only the relatively small off-chip
resistors are required to create a standardized
output that may be directly inputted to industry
standard pressure monitors without requiring an
interface device housed in a bulky box and inserted
between the catheter output receptacle and the input
to the monitors. To achieve the goal of matching the
output signal to standard pressure monitors in a
batch fabrication environment, the sensor is designed
to produce a nominally greater sensitivity than
expected by commercial monitors. The off-chip
resistor network is located in the receptacle or
electrical connector outside of the body and at the
proximal end of the catheter for use in reducing the
sensitivity of the pressure signal to a standardized
output specification.

Once the die and its associated electronics have
been fabricated, the die is encapsulated within the
distal end of a catheter. The material used to
encapsulate the die should be a medical grade
silicone or material with similar properties. In one
of the illustrated embodiments, the catheter is a
dual lumen design having a nominal wall thickness of
.005 inches. One lumen is dedicated to the
encapsulation of the die, and the second lumen is
open and large enough for fluid sampling or
injection, die injection, external pressure
monitoring or guidewire passage. The sensor lumen
extends beyond the guidewire lumen so that the sensor
may be mounted with the diaphragm centered under a

hole located in the flat center wall of the lumen
which faces the guidewire lumen. This feature allows
the sensor to measure pressure without the
possibility of being wedged against a vessel wall.
Side facing pressure measurement also eliminates the
erroneous inclusion in the pressure reading of the
kinetic energy term of the flowing blood.

During encapsulation, the reference pressure
V-groove which communicates the reference side of the
diaphragm to atmosphere is kept open and clear by
temporarily inserting a wire into the groove. The
wire is later retracted after the encapsulant is
cured. Atmospheric pressure is communicated to the
reference side of the diaphragm by way of the groove
and a hole in the electrical connector joining the
electrical lumen of the catheter to the monitoring
equipment.

The encapsulant material is chosen such that it
does not bond to the die but envelopes it so that
stresses applied to the catheter tip are effectively
absorbed by the encapsulant, thereby minimizing
stress on the die.

The thickness of the encapsulant over the
diaphragm can be uniformly controlled to eliminate
waveform distortion of the pressure transmitted
through the encapsulant to the diaphragm. The
encapsulant over the diaphragm serves to provide
electrical and environmental isolation between the
die and the interior of the cavity under examination
-- e.g., a blood vessel. To eliminate the transmis-
sion to the sensor of stresses due to catheter
flexing, the sensor may be surrounded by a suitable
rigid support, such as may be fabricated from
stainless steel tubing ground into a half-round
shape. This piece may be inserted into the catheter

lumen so as to provide a rigid support member around
the sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

While the invention will be described in
connection with the preferred embodiments, it will be
understood that it is not intended to limit the
invention to a particular embodiment. On the
contrary, it is intended to cover all alternatives
and equivalents as may be included within the spirit
and scope of the invention as defined by the appended
claims.

FIG. 1 is a magnified perspective view of a
sensor incorporating the invention, illustrating the
size of the sensor relative to a U.S. 10 cent coin;

FIG. 2(a) is a magnified plan view of the tip of
a conventional catheter incorporating the sensor of
FIG. 1;

FIG. 2(b) is a cross-sectional view of the
catheter and sensor of FIG. 2(a) taken along the line
2b-2b;

FIG. 2(c) is a cross-sectional view of the
catheter and sensor of FIG. 2(a) taken along the
line 2c-2c;

FIG. 3(a) is a magnified plan view of the tip of
a conventional catheter with a lumen for a guidewire
incorporating the sensor of FIG. 1;

FIG. 3(b) is a cross-sectional view of the
catheter and sensor of FIG. 3(a) taken along the line
3b-3b;

FIG. 3(c) is a cross-sectional view of the
catheter and sensor of FIG. 3(a) taken along the line
3c-3c;

FIG. 4 is a schematic diagram of a pressure
sensor monitoring system incorporating a pressure
sensor according to the invention;

15

FIG. 5 is a process flow diagram depicting the basic processing steps and the sequencing necessary to produce a set of pressure sensors according to the invention;

FIG. 6 is a plan view of a device wafer illustrating a plurality of diaphragms and sets of target holes used for alignment purposes in accordance with the invention;

FIG. 7 is a plan view of a backing wafer showing a pattern of grooves according to the invention;

FIG. 8 is a side view of the device and backing wafers of FIGS 6 and 7, respectively, taken along the lines 8-8 and showing etched targets, diaphragms, and grooves in proper relative alignment;

FIG. 9 is a magnified perspective view showing a sensor assembly with its device and backing dies separated;

FIG. 10 is a plan view of the surface of the device die illustrating the contacts, leads, and trim network which comprise the sensor;

FIG. 11 is a schematic diagram of the pressure sensor circuit; and

FIG. 12 is a side view of a pair of bonded dies for a sensor assembly according to an alternative embodiment of the invention wherein each of the two bonded dies serves both as a device and as a backing for the other die.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Turning to the drawings and referring first to FIG. 1, a sensor assembly 11 of an extremely small size is fabricated to function as a pressure sensor. To provide some appreciation for the small size of the die, a portion of a U.S. coin 13 of a 10 cent denomination (dime) is shown beside the

16

sensor assembly 11 in the same scale. Pressure
sensors of such small size may be mounted to
catheters or other suitable means (such as
guidewires). Vascular applications of the sensor
assembly 11 which are not served well by prior art
devices include entry into very small cavities, such
as adult coronary arteries or pediatric vessels, or
less traumatic entry into larger cavities, such as
heart chambers or peripheral vessels. Non-vascular
applications of the sensor assembly 11 include intra-
cranial and various gastrointestinal and urological
pressures. In general, a very small sensor-tipped
catheter may be utilized advantageously wherever
pressure waveform accuracy, patient safety, or
inaccessibility by other techniques is a significant
issue.

Exemplary embodiments of the sensor assembly in
a catheter are illustrated in FIGS. 2 and 3.
Referring first to the preferred embodiment of
FIGS. 2(a), (b) and (c), the sensor assembly 11 of
Fig. 1 is mounted in a conventional catheter 15
suitable for cardiovascular or other critical care
pressure monitoring, such as of size 2.5 to 4
French. The sensor assembly 11 is supported in the
catheter 15 in such a manner that the sensor is
sensitive to changes in the pressure within the
vessel (not shown), while insensitive to external
stresses imposed upon the catheter, such as from
vessel movement, and yet the sensor assembly is
protected from the environment of the blood or other
body fluid. This type of support may be accomplished
by proper design of a rigid sensor carrier 17 and use
of suitable encapsulation material 19.

Specifically, the sensor assembly 11 is secured
by adhesive 21 inside the cylindrically-shaped

carrier 15 which is inserted into the end of the
catheter 17. The carrier 17 may be formed from
stainless steel, ceramic, or other suitable
material. In general, the wall thickness of the
carrier 17 must be sufficient so that mechanical
stresses from insertion, catheter or vessel flexing,
or other sources are not transmitted to the sensor
assembly 11. A window 23 is provided in the
carrier 17 so that a pressure-sensitive diaphragm 25
of the sensor assembly 11 (formed by a cavity 26 in
the assembly) may communicate with the fluid sur-
rounding the catheter. Encapsulation material 19 is
a pressure coupling medium (e.g., an RTV silicone)
which allows for high fidelity transmission of
pressure variations to the sensor assembly 11 yet
provides environmental and electrical isolation of
the sensor from ambient body fluids. Catheter tip 20
is of rigid design and may be fabricated as an
integral part of carrier 17. Alternatively, catheter
tip 20 may be formed from various well-known epoxies
or other fluid impermeable materials. Tip 20
functions to present a smooth, bio-compatible finish
and moisture seal to the catheter interior. A
reference pressure cavity 26 of the sensor
assembly 11 communicates with an inner lumen 29 of
the catheter 15 through a bore 31 which extends
through the length of the sensor assembly 11 and
through lumen 27 of carrier 17. The inner lumen 29
is vented to room air pressure through a port in an
electrical connector (not shown in FIGS. 2a-2c) at
the proximal end of the catheter. Electrical
connection to the sensor assembly 11 is made via a
four-wire cable 33 bonded to pads (not shown in
FIGS. 2(a)-2(c)).

18

In the alternative packaging embodiment of
FIGS. 3(a)-3(c), the sensor assembly 11 of FIG. 1 is
contained within the lumen 35 of a double lumen
catheter 37. A second lumen 39 is available for
passage of a guidewire 41, such as would be used to
assist in placing the catheter 37 into a desired
location within a small vessel or in passing through
a cardiac valve or stenotic area. The lumen 39 may
also be used for sampling of blood or direct infusion
into the bloodstream. To reduce stress, the sensor
assembly 11 is secured to a rigid carrier 43 which
functions in a manner similar to carrier 17 of
FIGS. 2a-2c and which may be fabricated from the same
types of materials. As with the embodiment of FIGS.
2a-2c, a window 45 is provided to allow transmission
of pressure variations through a pressure coupling
medium 47 to the diaphragm 25 of the sensor 11. The
material comprising the pressure coupling medium 47
may be the same as that of the coupling medium 19 of
the FIGS. 2a-2c embodiment. A catheter tip 49
provides a function similar to that of the catheter
tip 20 of FIG. 2(c). Reference pressure to the
sensor assembly 11 is provided to the V-shaped bore
31 through inner lumen 35 which is vented to room air
pressure through a port in an electrical connector
(not shown). As with the embodiment of FIGS.
2(a)-2(c), the electrical connection to diagnostic
equipment is made via four-wire cable 33 bonded to
pads (not shown) on the sensor assembly 11.

A pressure sensor catheter such as that of
FIGS. 2 or 3 may be incorporated into a pressure
monitoring system for use in an intensive care
unit. In FIG. 4, a standard monitor 53 includes a
source 53a for excitation of the sensor 11 and a
meter 53b for displaying a pressure signal. An

electrical connector 55 contains a compensation
network 57 and serves to communicate excitation
signals from the source 53a to the pressure sensor
assembly 11 and pressure signals from the sensor to
the meter 53b via lines 33. The network 57
attenuates the pressure signals from the sensor
assembly 11 so they are of a standard sensitivity and
capable of direct transfer to the standard monitor
53. As explained more fully hereinafter, the
network 57 also functions to compensate the pressure
signals for pressure offset and changes in ambient
temperature, which cannot be compensated using only
the on-chip techniques provided by the invention. As
illustrated in FIG. 4, the sensor assembly 11
includes a Wheatstone bridge integrated circuit
comprising piezoresistors R_1, R_2, R_3 and R_4 and a
trim network 61. The trim network 61 provides an
offset adjustment for the bridge circuit, as well as
limited temperature compensation. As described more
fully hereinafter, the trim network 61 consists of a
thin film resistor ladder of metal chosen to have a
temperature coefficient of resistance (TCR)
comparable to the TCR of the piezoresistors R_1-R_4.

Pressure sensor assemblies fabricated in
accordance with the invention utilize the piezo-
resistive effect for sensing strain in the silicon
lattice of a diaphragm formed in the die comprising
the sensor, and this effect is most pronounced in
<100> silicon. In addition, formation of the thin
diaphragm in crystalline silicon is achieved by
selective chemical etching (thinning) of a defined
area of the die to a specified depth, with uniform
sidewall geometry. For this operation, <100> silicon
is also the material of choice. In the prior art,
pressure sensors are typically fabricated from a

single silicon wafer. In this connection,
conventional fabrication processes require a
sufficiently thick wafer such that structural
integrity is maintained during the processing steps;
typically a .012 - .015 inches or thicker wafer is
required in order to ensure adequate yield. In
conventional processing, the circuitry which com-
prises the sensing elements and their interconnec-
tions are processed into the wafer prior to the
chemical etching of the diaphragm. The thinning
process which forms the pressure-sensitive diaphragm
requires the use of an anisotropic etchant system
which selectively removes silicon along <111> crystal
planes at an angle of 54.7 degrees to the surface.
The wafer must be etched through almost to the
opposite surface in order to provide a sufficiently
flexible diaphragm. This etch angle, along with a
required area of non-etched silicon surrounding the
diaphragm for ensuring structural integrity,
effectively defines the minimum size of the
semiconductor die of the sensor assembly 11 which can
be achieved from a given starting wafer thickness.
These facts have typically limited prior art sensor
assemblies to relatively large die sizes that are
incompatible with packaging into catheters small and
flexible enough to be used in the very small body
cavities contemplated by the present invention.

In accordance with one important aspect of the
invention, a diaphragm is first etched into a thin
wafer (e.g., .003 inches) and thereafter immediately
bonded to a thicker silicon wafer (e.g., .008 inches
thick) to provide the structural support needed by
the first wafer containing the diaphragm in order to
prevent shattering of the diaphragm during further
processing steps. Subsequent to the bonding of the

two wafers, the other processing steps required to
fabricate the electronic circuitry are performed.
Processing the two wafers forming the dice separately
for certain key operations and then bonding them
together prior to the fabrication of the sensing
circuitry not only allows a very thin wafer to be
utilized for etching of diaphragms, but also allows
fabrication of a unique reference pressure venting
feature into the surface of the backing wafer prior
to bonding the two wafers together. After bonding,
the pressure vent communicates ambient pressure to
the cavity formed by the diaphragm through the side
of the sensor assembly instead of through the bottom
of an amorphous backing structure, as is typical of
prior art sensors. This feature is advantageous for
sensor assemblies designed to be incorporated into
small packages, such as catheters.

Turning to the fabrication of the sensor
assembly according to the invention, FIG. 5
illustrates a flow diagram of the important process
steps. As a first step (Step One in FIG. 5) a
silicon wafer is selected; for example, a two-inch
diameter, p-type <100> silicon wafer, 10 ohm-
centimeter resistivity, .003 ± 0.1 inches thickness,
polished both sides. As a second step (Step Two), an
epitaxial (epi) layer of silicon is grown of opposite
doping type to the wafer, so that a p-n junction is
formed by applying proper bias. The thickness of the
epi layer determines the final thickness of the
pressure sensitive diaphragm in the completed
sensor. An example of a specification for the epi
layer which complements the foregoing example for the
device wafer is 3.0 ± 0.2 microns, n-type doping,
10 ohm-centimeter.

22

In Step Three of the flow diagram, a pattern for
diaphragms and target holes is placed on the device
wafer. Diaphragm geometries may be square or
rectangular, and the population density on the wafer
may be varied. In accordance with another important
aspect of the invention, the target holes provide for
fabrication of economical sensors by allowing
alignment of sensor features without the use of
expensive special purpose equipment. Referring to
FIG. 6, there are two target areas 63 and 65 on the
device wafer 67 located opposite each other at the
periphery outside the diaphragm patterned area 69.
Each target area contains two types of targets. One
set of targets 71, consisting of one type from each
target area 63 and 65 of the wafer 67, is used to
align the device and backing wafers during the wafer-
wafer bonding process step. This alignment is
necessary because V-shaped grooves or channels in the
backing wafer must pass through the center of the
closed cavities formed by the diaphragms when the
wafers are bonded.

A second set of targets 73 provides alignment of
successive semiconductor layers to the diaphragms of
the device wafer 67 during the fabrication of
transduction devices. Such alignment is typically
carried out in conventional processing by the use of
a double-side optical or infrared mask aligner which
allows for the simultaneous viewing of features on
both sides of a wafer. This equipment is very
expensive and can typically be justified only for
those applications in which large quantities of
wafers are to be processed on a routine basis.

Typical target patterns of the present invention
are squares of dimension 250 x 250 microns for the
wafer alignment step (targets 71) and 160 x 160

microns for the layer alignment steps (targets 73),
although other sizes and geometries could be used.
Both sets of the targets 71 and 73 are patterned
along with the diaphragm patterns. During the
etching of the diaphragms in the silicon wafer, the
target patterns are also etched. Unlike the
diaphragms, however, the targets are etched com-
pletely through the silicon wafer 67 and appear on
the epi side as perfectly square openings. During
wafer-to-wafer bonding described hereinafter, the
larger openings formed by the first set of targets 71
are used to view directly, with a standard optical
microscope, the V-shaped grooves of the backing wafer
placed underneath. After the wafers are bonded, the
smaller openings visible from the epi surface and
formed by the second set of targets 73 are used along
with a standard mask alignment system to orient
subsequent mask patterns for the circuit fabrication
as discussed hereinafter. Each pattern mask contains
very fine (e.g., two micron wide) alignment reticles
(cross-hairs) which may be positioned through the
corners of these smaller openings. With this method,
alignment accuracies comparable to that of a double-
side optical or infrared aligner can be realized.

After the patterns for the targets and diaphragm
have been formed, the epi surface of the device wafer
67 is covered with a sputtered thin film of aluminum
in Step Four of FIG. 5 for use as an electrode
contact surface during the etch process. Other
metals compatible with the process line, such as
gold, could also be utilized.

In Step Five of FIG. 5, the device wafer 67 is
subjected to the process of selective chemical
etching to form small three dimensional structures
defining the targets and diaphragms, a conventional

24

process termed "micromachining" in the art. This
process is used typically to provide thin and
therefore flexible diaphragm structures for sensor
devices, and it is important since the performance
of silicon pressure sensors depends upon control over
the etched thickness of the diaphragm. Numerous
techniques to control the thickness of the diaphragm
exist in the prior art; for example, timed etch,
boron etch stop, infrared transmission, etc. One
of the best available techniques, termed "electro-
chemical etch stop," is well described. For example,
see T.N. Jackson, M.A. Tischler, and K.D. Wise, <u>IEEE</u>
<u>Electron Device Letters</u>, EDL-2, 44-46, 1981.

The technique of "electrochemical etch stop" is
conventionally described for etching diaphragms from
10-30 microns or more in thickness. For the present
application, however, a diaphragm thickness of three
microns is required, which to applicants' knowledge
has not been previously reported. To achieve such a
thin diaphragm, the silicon wafer 67 is placed into a
machined stainless steel fixture, which provides
mechanical support to the .003 inches thick wafer.
The surface on which the wafer 67 lies also serves as
a disk electrode for applying the proper electrical
bias to the epi (metallized) side. A silicone rubber
seal (not shown) covers the electrical contact side
of the wafer and isolates the opposite side of the
wafer containing the diaphragm pattern (to be etched)
from the electrical contact side. Failure to
maintain an absolute fluid seal over the electrical
contact side results in premature passivation of the
silicon wafer with consequent poor diaphragm
formation. Several chemical etchant systems could be
used; for example, a solution of hydrazine/water

(e.g., 50/50 by volume). From the foregoing discus-
sion, those skilled in the art of semiconductor
fabrication will readily appreciate that the fixture
and seal for the foregoing etch process are conven-
tional and their precise design a routine task.

The reaction is carried out in a reflux system
at or near the boiling point of the etchant (i.e.,
119°C for 50/50 hydrazine/water). Positive elec-
trical bias is supplied to the metallized surface of
the wafer via the fixture and a reference platinum
electrode is located in the etch bath. This allows
the p-n junction formed at the interface between the
n-type epi layer and the p-type wafer to be main-
tained in a reverse bias condition. The bias is
adjusted so that a current of three to four milli-
amperes flows while etching proceeds. For a
discussion of bias parameters, see R.L. Gealer,
H.K. Karsten, and S.M. Ward, J. Electrochemical
Society, 135, no. 5, 1180-11183, 1988. After etching
begins, it will proceed through non-passivated
silicon p-type material until there is no more p-type
material remaining (i.e., the epi surface is
reached). When the epi surface is exposed, a large
increase in current will occur, followed by a rapid
decrease in current as the epi surface becomes
passivated.

During the etching of the diaphragm, the two
sets of targets are also etched through the wafer and
halted at the epi surface. To etch the targets
through the epi surface, precautions must be taken to
protect the diaphragms from further etching. This
can be accomplished by replacing the top half of the
etch fixture with a silicone seal (not shown) of
conventional design which protects the diaphragm
surface area of the wafer from the etchant but

26

exposes the target areas. A second immersion of the
wafer into the etchant without bias for a brief
period etches the three micron epi layer completely,
resulting in clean square targets formed in the top
surface of the wafer.

Using conventional processing techniques, the
thin metal film applied to the wafer in Step Four is
removed in Step Six. In Step Seven, the etched
surface of the device wafer is prepared for the
bonding process of Step 12, as disclosed, for
example, in M. Shimbo, K. Furukawa, K. Fukuda, and
K. Tanzawa, J. Appl. Phys., 60(8), 2987-2989, 1986.
For proper preparation, the wafer surfaces to be
bonded must be thoroughly cleaned and treated to form
a hydrophilic layer.

Turning to the preparation of the backing wafer
starting at Step Eight in FIG. 5, a representative
specification for a silicon starting material for the
backing wafer is, for example, a two-inch diameter,
p-type <100> silicon wafer, having 10 ohm-centimeter
resistivity and .008 ± 0.3 inch thickness and being
polished on both sides.

In Step Nine of FIG. 5, patterns for channels in
the form of V-shaped grooves are placed on the backing
wafer. Each of the V-shaped grooves provides a bore 31
of the sensor assembly 1 (FIGS. 1-3). Each bore 31
functions to communicate a reference pressure through
the side of the wafer and to the cavity formed from the
diaphragm and closed by the wafer-to-wafer bonding.
FIG. 7 shows a backing wafer 75 with V-shaped grooves
31 etched into its surface prior to the wafer bonding
step. The grooves 31 extend the full length of wafer
75 and the spacing between grooves corresponds to the
center-to-center spacing of the corresponding diaphragm
pattern on the device wafer 67. Although applicants

27

presently form the V-shaped grooves 31 by using an
anisotropic etchant which self-stops at the inter-
section of <111> planes, it should be understood that
such a groove need not necessarily be V-shaped. Other
processes for forming the grooves may provide different
profile shapes; for example, the grooves could be
formed by a wafer dicing saw.

In the present invention, as an example, each
V-groove pattern is 100 microns wide, resulting in a
self-stopping etch depth of about 70 microns in
Step 10. The etch process is conventional; for
example, potassium hydroxide, self stopping at the
intersection of <111> planes. Prior to bonding with
the device wafer 67, the backing wafer 75 is prepared
for the bonding process in the same manner as defined
in Step Seven for the device wafer.

At some point in the fabrication of every
semiconductor pressure sensor, the sensor must be
attached to a backing material to provide structural
support. Such backing support inevitably leads to
degraded sensor performance over a given temperature
span of operation due to mismatches of thermal expan-
sion coefficients inherent to different materials
which cause stresses in the sensor structure. In the
prior art, the backing material is typically glass,
or, preferably, another silicon wafer utilizing a
bonding agent, such as a layer of silicon dioxide,
followed by an annealing treatment. Direct silicon-
to-silicon bonding is considered most advantageous
since no third material is present. In Step 12 of
the present invention, such a direct silicon-to-
silicon bond is achieved. A technique similar to
that referenced in Step Seven is utilized to effect
the desired bonding and is considered conventional.

28

In connection with Step 12, FIG. 8 is a side
view of the device and backing wafers 67 and 75,
respectively, showing etched targets 71 and 73,
diaphragms 25, and V-shaped grooves 31 in proper
relative alignment. Proper alignment of the wafers
67 and 75 during fabrication centers the V-shaped
grooves 31 in the cavities formed by the
diaphragms. Preferably, an optical microscope is
employed to directly view the backing wafer 75
through the holes of the targets 17. The backing
wafer 75 is positioned so that V-grooves 31 are
directly under the targets 71 as suggested by the
alignment of the wafers in FIG. 8.

In Step 13, the piezoresistor pattern is defined
on the epi surface, utilizing the second set of
target patterns formed in Step Five. Subsequently,
the piezoresistors R_1-R_3 are formed via conventional
ion implantation equipment and driven in by heat
treatment. The ion dose delivered and the drive-in
recipe are considered conventional, with special
consideration, as discussed in a later paragraph, on
their contribution to temperature compensation. As
is known in the art, any set of stated dose
parameters, if defined for a given set of equipment,
must be experimentally verified if utilized on other
equipment.

In Step 14, the P+ layer which forms the
electrical connections to the piezoresistors R_1-R_4 is
patterned, implanted, and annealed, all by
conventional processing methods. In Step 15, the
contact openings are formed which are necessary to
allow connection of the P+ layer to the thin film
aluminum tracks of Step 16. As with Step 14, this is
conventional processing methodology required of any
integrated circuit process.

29

In Step 16, the metallization pattern is
defined, deposited and etched. This pattern includes
resistor interconnects for piezoresistors R_1-R_4,
electrical contact pads for bonding the wires, and
the trim network 61. The process steps are
considered conventional. The choice of metal and the
thickness of deposition have an effect on the overall
temperature compensation achieved on-chip, and are
further discussed in a later paragraph.

The process step in Step 17 is conventional and
includes the provision of a passivation layer over
the surface of the device wafer 67 for environmental
protection, as well as subsequent opening of windows
over the bonding pads. After all processing is
complete, the bonded wafers 67 and 75 are sawn into
individual sensor die by a conventional wafer dicing
process in step 18.

As previously mentioned, the foregoing
Steps 13-17 employ the targets 73 in conjunction with
a standard mask alignment system to orient the
various patterns on the device wafer 67. The
targets 73 ensure the proper placement of the fabri-
cated circuit elements relative to the pattern 69 of
diaphragms (FIG. 6) on the device wafer 67.

FIG. 9 is a magnified perspective view of a
sensor die 81 sawn from the bonded wafers of FIG. 8,
showing the sensor die and its component parts.
V-shaped groove 31 of backing die 81a is centered in
the cavity of diaphragm 25 of the device die 81b.
Other features include contact pads 83, the trim
network 61, and trim pads 85. FIG. 10 shows the
completed sensor die with interconnects 87 for
forming a Wheatstone bridge network from the piezo-
resistors R_1-R_4. Fusible links 89 function to allow
portions of the trim network 61 to be selectively

added to the bridge circuit formed by the piezo-
resistors R_1-R_4. Links 89 may be selectively removed
by application of a suitable electrical current
between two adjacent trim pads 85.

Referring to the schematic diagram of the sensor
circuit in FIG. 11, excitation source 53a and meter
53b of the standard monitoring equipment 53 of FIG. 4
are connected to the the sensor circuit formed by the
sensor die 81. Piezoresistors R_1, R_2, and R_4,
nominally the same value, and piezoresistor R_3,
chosen to be slightly higher in value, form a full
Wheatstone bridge and are physically located upon the
diaphragm 25 as illustrated in FIG. 10. As the
diaphragm 25 is stressed, the resistors R_1-R_4 change
value due to the piezoresistive effect, resulting in
a bridge imbalance detected by meter 53b. Variations
in the values of the unstressed piezoresistors R_1-R_4
due to normal fabrication process tolerances will
generally result in an imbalance at zero pressure.
In this case, the trim network 61 can be utilized to
increase the value of resistor R_4 in incremental
steps of resistance r_0 until balance is achieved.
Adjustment of the effective resistance provided by
the trim network 61 is made by removing combinations
of shorting links 89 by passing electrical current
through the links via pads 85. In addition, since
piezoresistor R_3 is fabricated to be larger in value
than the other resistors R_1, R_2, and R_4, resulting in
a nominal non-zero voltage at zero relative pressure,
the trim network 61 can be utilized to remove both
positive and negative imbalances.

To provide a stable output signal which is
reliable over a full range of expected temperatures,
two different but related phenomenon must be con-
sidered. First, as is well known in the art, the

value of the resistance for each piezoresistor R_1-R_4
implanted in the wafer 67 is a function of the
ambient temperature. Second, as is also well known
in the art, the value of the piezoresistive coeffi-
cient is a function of the ambient temperature. The
first phenomenon is quantified as a temperature
coefficient of resistance (TCR), and the second is
quantified as a temperature coefficient of the piezo-
resistive coefficient (TCPI). In practice, the TCR
affects the zero offset of the output signal from the
sensor, and the TCPI affects the sensitivity of the
piezoresistors. An uncompensated change in the TCPI
will cause a change in the magnitude of the output
signal from the piezoresistive bridge network,
assuming a static pressure differential across the
diaphragm 25. Typically, the sensitivity of the
piezoresistive bridge network decreases with
increasing temperature and the nominal value of the
resistance of the network increases.

Typical mechanisms for compensating for the
change in sensitivity caused by the TCPI include the
use of constant current excitation with controlled
TCR values to compensate for the loss of sensi-
tivity. J. Bryzek, "Approaching Performance Limits
In Silicon Piezoresistive Pressure Sensors," Sensors
and Actuators, 4 (1983); M. Poppinger, "Silicon
Diaphragm Pressure Sensors," Solid State Devices
1985, Elsevier Science Publishers B.V., 1986. As an
alternative to the use of constant current excita-
tion, external active circuits have been used.
Samaun, K.D. Wise, and J.B. Angell, "An IC Piezo-
resistive Pressure Sensor for Biomedical Instru-
mentation," IEEE Transactions On Biomedical
Engineering, Volume BME-20, No. 2, March 1973.
Because the sensor assembly 11 is intended to be

32

compatible with existing blood pressure amplifiers,
the use of constant current excitation is not an
acceptable mechanism for temperature compensation.
Furthermore, external active circuits are expensive
and are not in keeping with the object of the
invention to provide a low cost device.

In accordance with another important aspect of
the invention, the TCPI-dependent effects on the
sensitivity of the sensor assembly 11 may be
compensated for with the use of the external
compensation network 57 and an on-chip TCR value
which complements the value of the on-chip TCPI.
Specifically, the piezoresistors R_1-R_4 comprising the
bridge network are fabricated to have TCR and TCPI
values which complement each other in the following
manner: As the piezoresistive response of the
piezoresistors R_1-R_4 changes in response to the
temperature changes, the effective voltage applied
across the bridge network is increased in a manner
that results in a net zero change in the magnitude of
the output signal. By way of illustration, the
compensation network 57 composed of passive resistor
elements and the network of piezoresistors R_1-R_4 can
be modeled as a resistive ladder comprising in series
a first external resistor R_1, the network of piezo-
resistors RB and a second external resistor R_2.
Using Ohm's law, the voltage VE across the bridge
network equals,

$$VE = \frac{RB}{R_1 + R_2 + RB} \times V_0 \tag{1}$$

where V_0 is the voltage applied from conventional
monitoring equipment. The value of the bridge
resistance RB is a function of the TCR. From
equation (1), it is readily apparent that the value

33

of the voltage VE is related to the value of the
bridge resistance RB and, therefore, the TCR effects
the value of VE. When correctly calibrated, the
sensor assembly 11 should provide five microvolts per
volt excitation for every mmHg of pressure across the
diaphragm 25. With a change of temperature, the
sensor assembly 11 may provide, for example, only
4.5 μv/V/mmHg. However, the same temperature change
causing the sensitivity of the piezoresistors R_1-R_4
to decrease also causes the resistance RB of the
bridge network to increase. Because the response of
the piezoresistive bridge network is not only a
function of the TCPI, but also of the applied voltage
VE across the bridge, the proper selection of the TCR
of the bridge can cause a change in VE which will
offset the effect of the TCPI.

As fabricated, the sensor assembly 11 has a
theoretical piezoresistive response of greater than
the five μv/V/mmHG standard used by conventional
monitoring equipment; therefore, the compensation
network 57 connected in series with the
piezoresistive bridge network is also useful in
attenuating the sensitivity. The resistors of the
compensation network 57 are provided off-chip in
accordance with the invention and have several
advantages: namely, they allow sensitivity
calibration after final assembly; they simplify IC
fabrication; and they reduce on-chip power dissipa-
tion. These off-chip resistors also cooperate with
the TCR of the piezoresistive bridge network to
provide temperature compensation for the effects of
the TCPI.

The value for these off-chip resistors (herein-
after called "Rspan" resistors) to properly scale the
sensitivity of the sensor is easily calculated. By

34

selecting the value of the TCR for the off-chip
resistors Rspan to be zero, an equation may be
derived to select a TCR value for the piezoresistors
R_1-R_4 which corrects for the change of sensitivity as
a function of temperature due to TCPI.

$$TCR = [2Rspan/((2Rspan+RB)(1+TCPI)-Rspan)] - 1 \quad (2)$$

By choosing a fabrication process which results in a
TCR as close as possible to the value calculated by
Equation (2), a device is produced having an
acceptable temperature compensated sensitivity.

For a given fabrication process, the TCR of
p-type resistors R_1-R_4 in the piezoresistive bridge
may be approximated from available equations. The
sheet resistance (Rs) is a function of acceptor dose
and hole mobility. The change of the sheet resis-
tance (Rs) caused by a change of temperature is due
to the temperature dependence of hole mobility, and
equations approximating hole mobility as a function
of acceptor ion concentration (controlled in the
fabrication process) and temperature are known and
published in, for example, N.D. Arora, J.R. Hauser,
and D.J. Roulston, "Electron and Hole Mobilities in
Silicon as a Function of Concentration and
Temperature," IEEE Transactions on Electron Devices,
Volume ED-29, No. 2, February 1983.

The temperature coefficient of resistance (TCR)
for a given fabrication process can be predicted by
calculating the sheet resistance (Rs) at temperatures
T and T+1:

$$TCR = (Rs(T+1) - Rs(T))/Rs(T) \quad (3)$$

35

With the calculated values of the sheet resistance
(Rs) as a starting point, the TCR is experimentally
verified for a given fabrication process.

As is the case with TCR approximations, the
value of TCPI for a given fabrication process may be
mathematically approximated by available equations
such as, for example, Ki Won Lee, "Modeling and
Simulation of Solid-State Pressure Sensors," Ph.D.
Dissertation, University of Michigan, Ann Arbor,
1982. The calculated value of TCPI may be used in
Equation (2) to calculate the desired value of TCR.
Actual experimental verification may be required to
confirm expected results.

In addition to choosing the appropriate doping
level to achieve complementary TCR and TCPI values,
the preferred doping level also provides a piezo-
resistive coefficient that results in a high pressure
sensitivity (i.e., sensitivity compatible with
standard equipment) while maintaining minimum
sensitivity of the piezoresistive coefficient to
small variances in the doping levels which result
from normal fabrication tolerances. Finding the
preferred doping level is a technique which is well
known in the art of fabrication processes.

Normal variations in the fabrication process
also result in slightly different nominal resistance
values for the piezoresistors R_1-R_4, thereby causing
an offset of the output voltage from the
piezoresistive bridge network. As previously
mentioned, to provide the ability to trim the zero-
pressure offset voltage, one of the piezoresistors
R_1-R_4 is deliberately fabricated to have a slightly
greater nominal resistance than the others. In the
illustrated embodiment, this piezoresistor is R_3.
The piezoresistor R_4 is in series with a thin film

36

resistance of the trim network 61. The resistances
of the thin film may be selectively inserted so as to
cause the series value of R_4 and the trim network 61
to approach the value of R_3.

The effective resistance of the trim network 61
is adjusted by opening fusible links 89 with either a
pulse of current or a laser. The network 61 forms a
resistive ladder configuration (see FIG. 11) wherein
the links 89 shunt resistive elements r_0. As links
89 are selectively opened, the resistance of the trim
network 61 increases.

The trim network 61 is fabricated from an
aluminum alloy containing one percent silicon.
This material is commonly used in IC technology
for electrical pads and connecting tracks, and
is characterized by a TCR of approximately that
calculated by Equation (2). In this regard, the
TCR of the thin film network 61 matches that of the
piezoresistors R_1-R_4 and consequently the thin film
network does not contribute significantly to
thermally induced offset errors.

Other design and fabrication considerations for
the sensor assembly 11 are well known in the art.
For example, because the piezoresistors R_1-R_4 are
fabricated in close proximity to one another, their
resistances track each other well. Because the
sensor assembly 11 operates in an environment of a
limited temperature range (i.e., 15 to 45°C.),
junction leakage current is not a problem. Also,
thermally-induced stress at the junctions between
silicon of the wafer 67 and the silicon dioxide of
the piezoresistors R_1-R_4 is minimized by keeping the
silicon dioxide layer thin.

An alternative embodiment of the invention is
illustrated in FIG. 12 wherein each of two bonded

dies 91 and 93 serves both a device and a backing
function. In this case, a single assembly 95
contains two diaphragms 97 and their associated
V-grooves 99. Diaphragm 97 of one die 91 defines a
first sensor and a second diaphragm 97 of die 93
defines a second sensor on the opposite surface of
the assembly 95. Such an arrangement would be useful
in fabrication of a special purpose catheter designed
to measure pressure gradients along a vessel length,
such as across a stenosis or valve. Such an assembly
could be located in one lumen of a double lumen
catheter, with one sensor facing directly into the
vessel lumen through a suitable opening of the outer
catheter wall and the other sensor facing the second
catheter lumen through an opening in the center
wall. This second sensor measures pressure as
transmitted through the fluid column existing between
the tip of the catheter and the site of placement of
the sensor within the catheter. The pressure
gradient existing between the tip of the catheter and
the location of the sensor assembly is recorded as
the difference between the outputs of the two
sensors.

From the foregoing, it will be appreciated that
a miniaturized pressure sensor assembly 11 is pro-
vided which is adapted for placement at the tip of a
conventional catheter such as the catheters shown in
FIGS.2a-2c and FIGS. 3a-3c. By fabricating the
sensor assembly 11 in accordance with the invention,
a unique sensor structure is provided which allows
miniaturization to an extent previously unknown in
the art. By utilizing targets formed in the wafers
from which the assembly 11 is fabricated, the
fabrication process can be completed without the need
for expensive alignment equipment, thereby allowing

38

the sensor assembly to be manufactured relatively
inexpensively. Furthermore, the temperature
compensation techniques employed in connection with
the pressure sensor assembly 11 allow the device to
perform with high reliability over the temperature
range of its expected environment. Embodiments of
the invention other than in the pressure sensor
assembly 11 shown in FIGS. 1-11 are suggested by the
alternative embodiment of the invention shown in
FIG. 12. Those skilled in the art of pressure
sensing apparatus for recording physiological
pressure will appreciate that still other alternative
embodiments for the invention are possible.

39

We claim:

1. A pressure sensitive transducer device
adapted to be enclosed within the tip of a catheter
or the like for insertion into a small cavity, said
transducer comprises:

a device die composed from a thin wafer material
of uniform thickness, said device die having a cavity
opening to a first side of said device die and
forming a diaphragm etched out of said device die,
wherein said diaphragm contains piezoresistive
elements which change their characteristic
resistances in response to very slight changes in
stress on the diaphragm produced by a pressure
differential across said diaphragm;

a backing die composed of a crystalline
material, said backing die having a first surface
bonded to said first surface of said device die so as
to close said cavity between said backing and said
device dies;

a groove in said first side of said backing
die for providing a vent for said closed cavity to a
reference pressure source;

whereby the resistive changes in said
piezoresistive elements of said diaphragm are
monitored to produce a signal which represents the
differential pressure across said diaphragm.

2. A pressure sensitive transducer device
according to claim 1 wherein said piezoresistive
elements form a bridge network which includes a
resistive trim network for adjusting the nominal
resistive parameters of said bridge network.

3. A pressure sensitive transducer device according to claim 2 wherein said resistive trim network comprises a thin film resistor shunted by series connected fusible links.

4. A pressure sensitive transducer device according to claim 2 wherein the temperature coefficient of resistance (TCR) of said resistive trim network is substantially the same as the temperature coefficient of resistance (TCR) of said piezoresistive elements.

5. A method of manufacturing pressure sensitive transducer devices comprising the steps of:

processing a first thin wafer of crystalline structure to form a pattern of diaphragms comprising a plurality of rows;

processing a second thin wafer of crystalline structure to include a pattern of small channels formed along a first surface of said second thin wafer;

bonding said first and second thin wafers such that each of said channels of said second thin wafer is aligned with one row of said pattern of diaphragms of said first thin wafer and in communication with a closed cavity formed by each of said diaphragms in said one row;

processing the bonded first and second thin wafers to form electrical circuits to perform pressure transduction in association with said diaphragms; and

cutting the bonded first and second wafers into a plurality of individual pressure sensitive transducer devices.

41

6. A method as set forth in claim 5 wherein the step of processing said first thin wafer includes etching target holes through said first thin wafer and the step of bonding said first and second thin wafers includes the step of aligning said channels of said second thin wafer and said pattern of diaphragms of said first thin wafer by referencing said target holes to said channels.

7. A method as set forth in claim 5 wherein the step of processing said first thin wafer includes etching target holes through said first thin wafer and the step of processing the bonded first and second thin wafers includes placing pressure transducing devices on said bonded first and second thin wafers by referencing the fabrication of said devices to said target holes.

8. A process of fabricating semiconductor devices comprising the steps of:
   processing a first wafer of crystalline structure to create a feature of said semiconductor device in said first wafer and a set of holes in the perimeter of said first wafer;
   processing a second wafer of crystalline structure to create a feature of said semiconductor device in said second wafer;
   aligning said first and second wafers for bonding by using said at least two holes in said first wafer as a guide so said features of said semiconductor devices of said first and second wafers have a predetermined spatial relationship when said first and second wafers are bonded;
   bonding said first and second wafers; and

processing said bonded first and second
wafers to provide a plurality of semiconductor
devices.

9. A process as set forth in claim 8 wherein
said processing said bonded first and second wafers
includes the step of using said set of holes in said
perimeter of said first wafer as a reference for
aligning the fabrication of semiconductor junctions
and the placement of conductive strips.

10. A process as set forth in claim 8 wherein
the step of processing said first wafer includes
growing an epitaxial layer on said first wafer and
etching said first wafer to said epitaxial layer in a
manner that results in said feature being a plurality
of cavities forming diaphragms.

11. A process as set forth in claim 8 wherein
said step of processing said second wafer includes
the step of forming a plurality of parallel grooves
in said second wafer.

12. A process as set forth in claim 9 wherein
the step of fabricating semiconductor junctions and
conductive strips includes the step of matching TCR
and TCPI values to provide a sensitivity of said
semiconductor devices which is substantially
independent of temperature for the expected
temperature range of the intended environment for the
semiconductor device.

13. A process as set forth in claim 8 wherein
said processing of said bonded first and second
wafers includes substantially all the fabrication

43

involving the doping of said first or second wafers
and placement of conductive or resistive metallic
strips onto the surface of said first or second
wafers in order to realize said semiconductor device.

14. A process of fabricating semiconductor
devices comprising the steps of:
    processing a first wafer of crystalline
structure to create a feature in a first side of said
first wafer and a first set of holes in the perimeter
of said first wafer having a known spatial
relationship to said feature;
    fabricating a circuit on a second side of
said first wafer and precisely locating the elements
of said circuit relative to said feature by using
said set of holes as a reference so as to provide a
plurality of said semiconductor devices.

15. A process as set forth in claim 14 including
the steps of:
    processing a second wafer of crystalline
structure to create a feature in a first side of said
second wafer; and
    bonding said first side of said first and
second wafers before fabricating said circuit on said
second side of said first wafer.

16. A process as set forth in claim 15 wherein
precise spatial relationships are maintained between
said features of said first and second wafers during
bonding of said first and second wafers by using said
set of holes as a reference for aligning said first
and second wafers.

17. A process as set forth in claim 14 wherein said step of fabricating a circuit on said second side of said first wafer includes the step of providing matching TCR and TPCI values for said elements of said circuit such that the sensitivity of each semiconductor device is substantially independent of temperature for the expected temperature range of the device's intended environment.
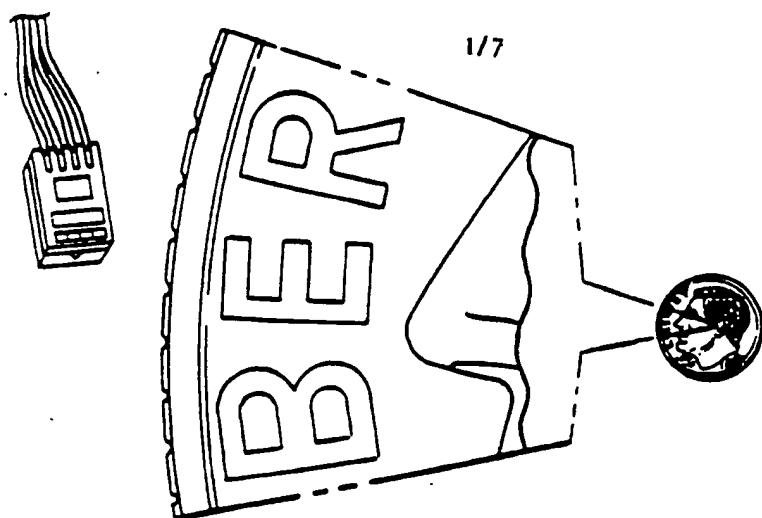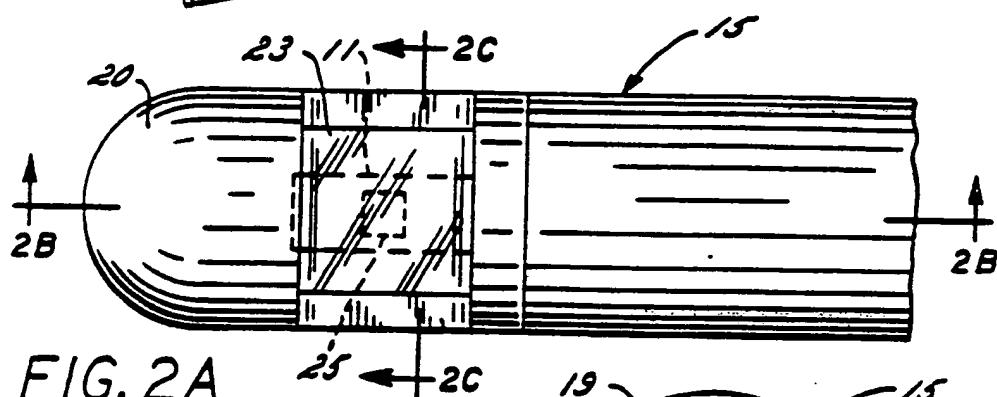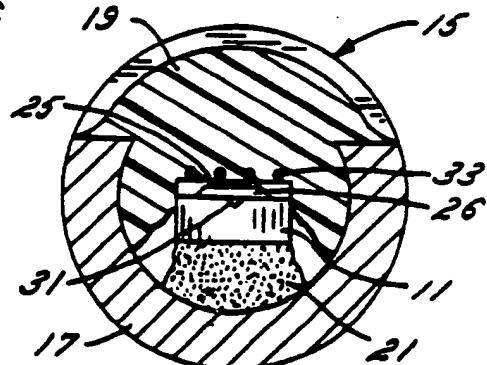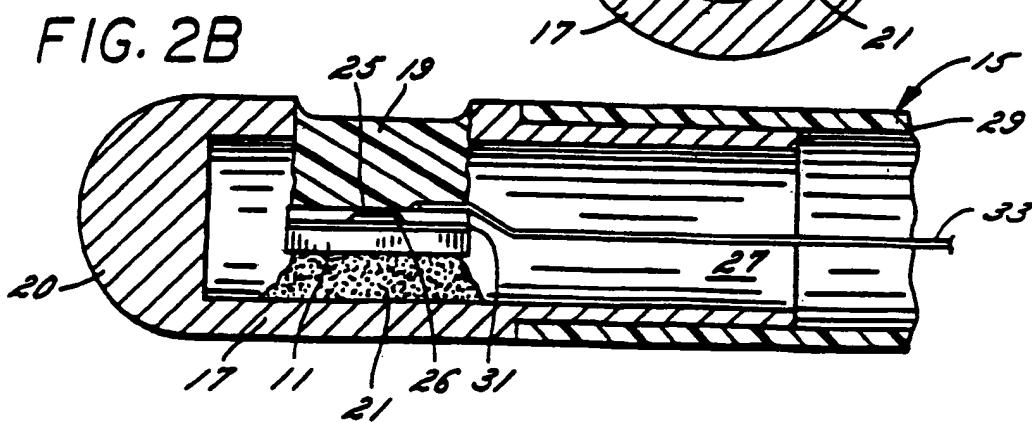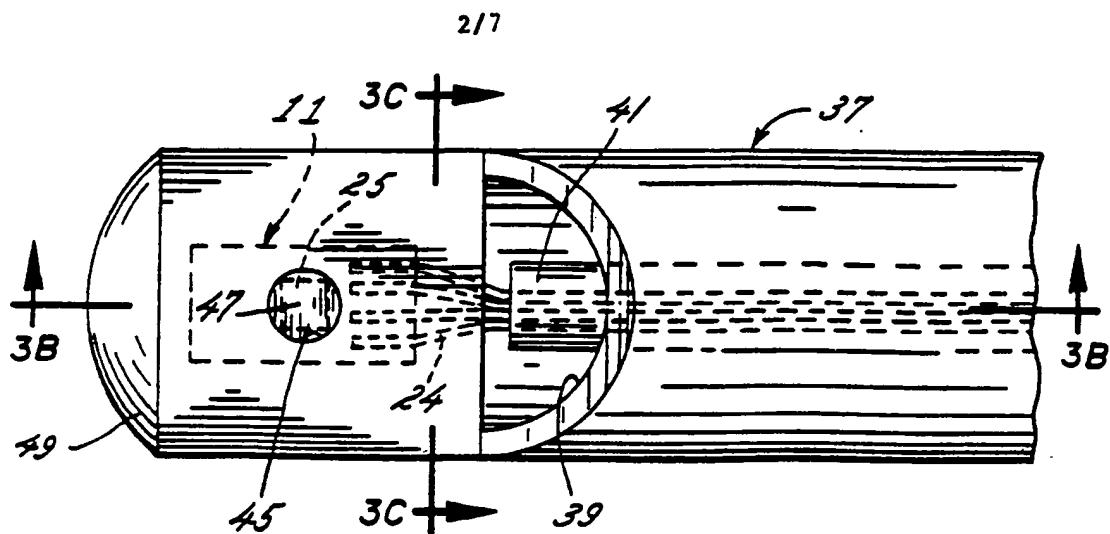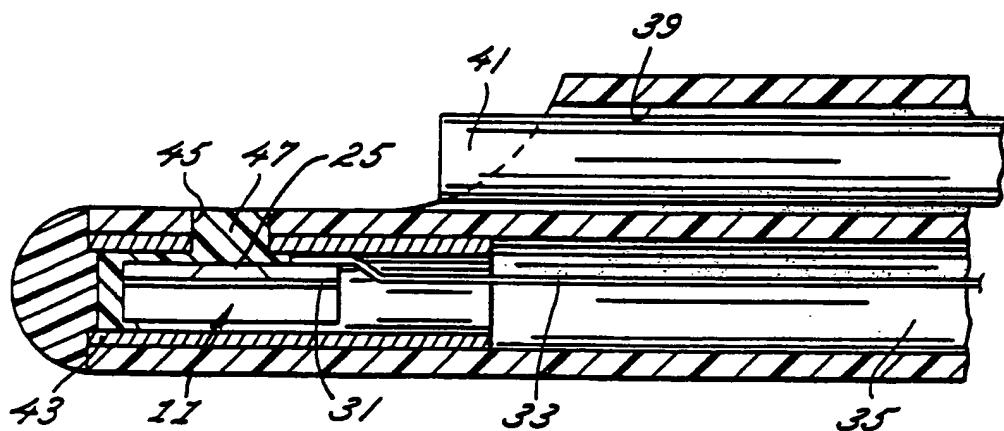
1/7

FIG. 1

FIG. 2A

FIG. 2C

FIG. 2B

FIG. 3A

FIG. 3B

FIG. 3C

FIG. 4

FIG. 12

4/7

STEP 1
```
SELECT
DEVICE WAFER
```

STEP 2
```
GROW EPITAXIAL
LAYER ON FIRST
SIDE
```

STEP 3
```
PATTERN
DIAPHRAGMS/
TARGETS ON
SECOND SIDE
```

STEP 4
```
METALIZE
FIRST SIDE
```

STEP 5
```
ETCH SECOND
SIDE TO FORM
DIAPHRAGMS
AND TARGETS
```

STEP 6
```
ETCH METAL
LAYER FROM
FIRST SIDE
```

STEP 7
```
PREP FOR
WAFER-WAFER
BONDING
```

STEP 8
```
SELECT
BACKING WAFER
```

STEP 9
```
PATTERN CHANNELS
ON FIRST SIDE
```

STEP 10
```
ETCH
CHANNELS
```

STEP 11
```
PREP FOR
WAFER-WAFER
BONDING
```

STEP 12
```
ALIGN AND
BOND DEVICE
AND BACKING
WAFERS
```

STEP 13
```
PATTERN,
IMPLANT AND
ANNEAL
PIEZORESISTORS
```

STEP 14
```
PATTERN,
IMPLANT AND
ANNEAL
P+ CONTACTS
```

STEP 15
```
FORM CONTACT
OPENINGS
```

STEP 16
```
DEPOSIT,
PATTERN AND
ETCH METALIZATION
LAYER
```
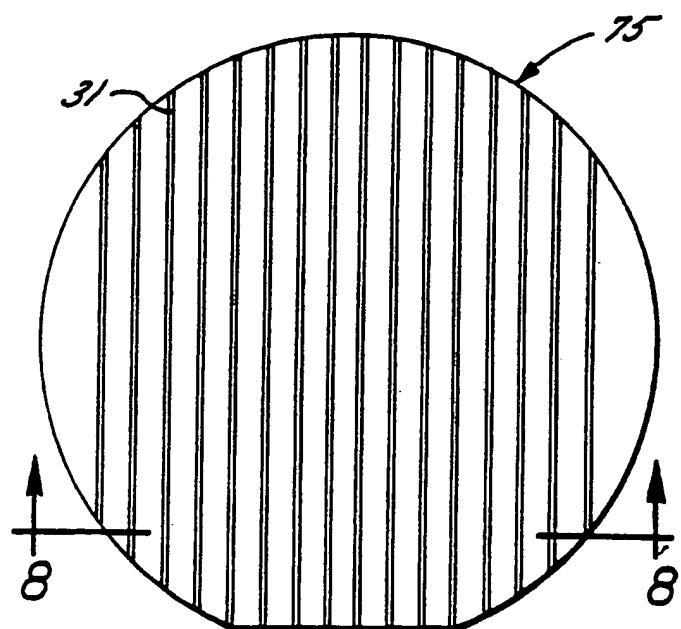
STEP 17
```
APPLY
PASSIVATION
LAYER
```
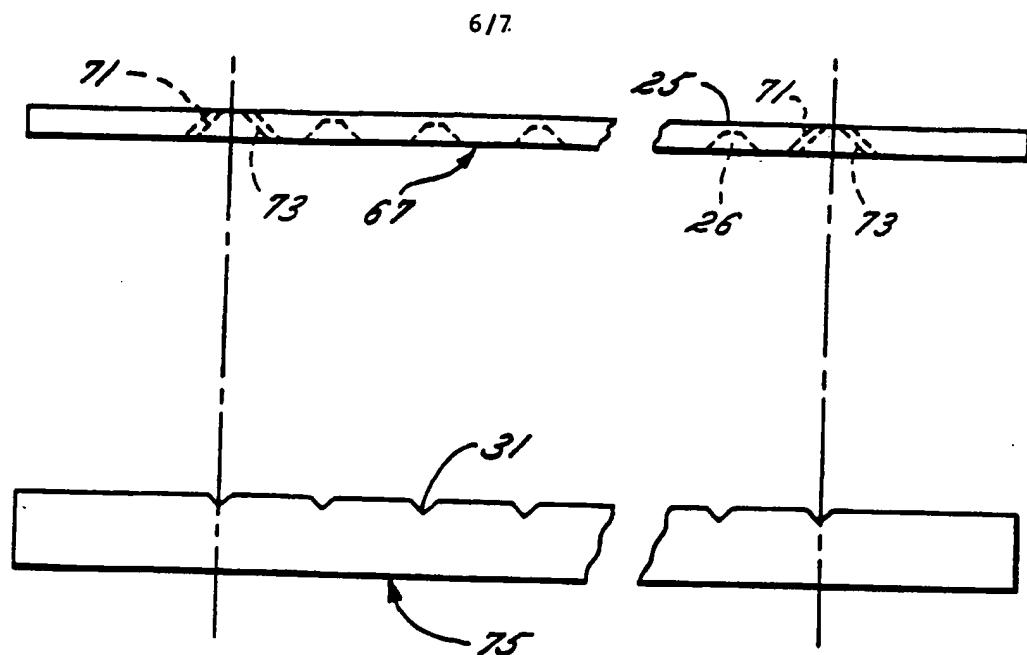
STEP 18
```
WAFER
DICING
```

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

INTERNATIONAL SEARCH REPORT

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) 6

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(5)   A61B 5/0215
U.S. Cl. 128/675,748   29/621.1

II. FIELDS SEARCHED

Minimum Documentation Searched 7

Classification System	Classification Symbols
U.S.	128/672,673,674,675,748 73/720,721,726,727,777 29/621.1

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched 8

III. DOCUMENTS CONSIDERED TO BE RELEVANT 9

Category *	Citation of Document, 11 with indication, where appropriate, of the relevant passages 12	Relevant to Claim No. 13
Y	US, A, 4,722,348 (LIGTENBERG) 02 February 1988. See the entire document.	1-4
Y	US, A, 4,766,666 (SUGIYAMA) 30 August 1988. See the entire document.	1-4
Y	1 EEE Transactions on Biomedical Engineering, vol. BME-33, no. 2, (SMITH ET AL.), "Analysis, Design, and Performance of a Capacitive Pressure Sensor 1C".	2-4
A,P	US, A, 4,809,704 (SOGAWA) 07 March 1989. See the entire document.	1-17
A	"Bonding Techniques for Microsensors" Micromachining and Micropackaging of Transducers, (KO) 1985. See the entire document.	5-17
A	Journal of Applied Physiology, "Siticon to Siticon Direct Bonding Method" (SHIMBO) 15 October 1986. See the entire document.	5-17

* Special categories of cited documents: 10

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

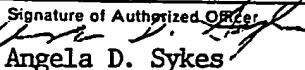| Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
03 March 1990	3 0 MAR 1990
International Searching Authority ISA/US	Signature of Authorized Officer Angela D. Sykes